Using Tunnel Boring Machine Penetration Tests to Quantify Performance in Hard Rock

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Keywords: penetration rate, geological characteristics, grinding, chipping, face stability

ABSTRACT

Tunnel boring machine (TBM) penetration tests entail incrementally increasing TBM thrust from full stop to maximum speed and recording the penetration rate either at set thrust levels or at set times. TBM penetration test data can be analysed by plotting the penetration rate (distance/revolution) against the net cutter thrust (force per cutter) over the full range of thrust levels in the test, called the penetration-thrust graph. This research shows that the transition from excavation dominated by grinding to excavation dominated by chipping can be observed in penetration-thrust graphs. Correlating penetration test data to the geological and geomechanical characteristics of rock masses through which a penetration test is conducted provides the ability to reveal the efficiency of the chipping process in response to changing geological conditions. By analysing penetration test data from projects in the Swiss Alps, and published data from Singapore, this research shows that the strength of the rock is an important control on how much net cutter thrust is required to transition from grinding to chipping. It also shows that the geological characteristics of a rock will determine how efficiently chipping occurs once it has begun. In particular, geological characteristics that lead to efficient fracture propagation, such as fabric and mica content, will lead to efficient chipping. These findings will enable a better correlation between TBM performance and geological conditions for use in TBM design, as a basis for contractual payments where penetration rate dominates the excavation cycle and in further academic investigations into the TBM excavation process.

1 INTRODUCTION

During hard rock tunnel boring machine excavation, a cutter first creates a crushed zone at the cutter-rock interface and the stresses from the thrust of the cutter are transmitted through this crushed zone into the adjacent undamaged rock (Figure 1). The induced stresses and dilation within the crushed zone cause extensile fracturing of the rock away from the crushed zone. Eventually, fractures generated by subsequent cutter passes extend either to the rock surface or to fractures propagating from adjoining kerfs and coalesce to form chips. This occurs at different cutter thrust magnitudes for different rock types. If the cutter thrust necessary for tensile fracture propagation is not achieved, due to excessively high cutter thrust requirements or an underpowered TBM, then only grinding at the crushed zone occurs. Grinding produces fines, rather than chips, leading to much lower penetration rate. Chipping is a more efficient excavation process because generating chips through tensile fracturing is much more efficient than the formation of fines in the crushed zone (Teale, 1964; Snowdon et al., 1982; Bruland, 1998; Gertsch et al., 2007; Yin et al., 2014). The formation of chips by the chipping process is, therefore, critical for achieving high penetration rates.

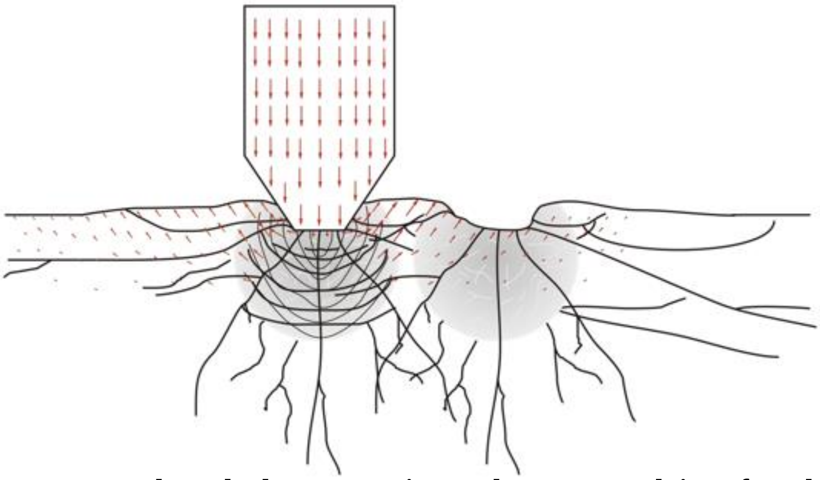

Figure 1: Fracture and crushed zone creation at the cutter-rock interface during TBM excavation (modified from Villeneuve, 2008).

This research demonstrates what TBM penetration testing can show about the excavation process. Based on work by Villeneuve (2008, 2017) and Frenzel et al. (2012), penetration tests are defined and index values are demonstrated for TBM performance analysis. Geological characteristics are linked to the chipping process identified with the penetration tests. TBM operational data and results from penetration tests are analysed to provide feedback about whether excavation is occurring efficiently through chipping or inefficiently through grinding.

2 PENETRATION TESTS

Villeneuve (2017) performed a total of 16 penetration tests in three different rock units in the Swiss Alps: schist (Figure 2), granite (Figure 3) and gneiss (Figure 4). Figure 4 also includes data for marble and granite from Yin et al. (2014) and Gong et al. (2007). The tests in the Swiss Alps were undertaken using three Herrenknecht hard rock gripper TBMs with a diameter range of 8.83-9.58 m. All TBMs utilised 432 mm diameter cutters with 90 mm spacing on centre. During normal TBM start-up only a few data points at low penetration rates were recorded by the data acquisition system (DAS) due to the sampling interval (typically 1/10 s). In order to capture sufficient data through the full range of penetration rates, penetration tests were adopted (Villeneuve, 2008; later described in detail in Frenzel et al., 2012), and conducted by gradually increasing the TBM thrust from full stop to the maximum thrust over a period of 8-10 min. The cutterhead rotational speed (RPM) was kept constant during these tests, typically ranging from 5.5 rpm to 6.2 rpm, and was selected based on the face condition (i.e. it would be higher in stable face conditions than in blocky face conditions). Depending on the operator, RPM and rock type, the length of tunnel tested is approximately 30-200 mm.

The penetration rate (mm/rev) was used in Villeneuve (2017), rather than speed (mm/min), because this removes the effect of RPM and allows comparison of test results from different strokes. The thrust value obtained from the DAS is gross thrust, which is the amount of force exerted by the thrust pistons. This thrust incorporates friction on the TBM head, which is independent of cutting processes occurring at the tunnel face. The net cutter thrust is used, which is the gross thrust minus the frictional losses, divided by the number of cutters, to allow comparison of test results from different locations and different TBMs. The friction contribution to gross thrust is estimated by averaging the gross thrust required to reverse and advance the TBM cutterhead (i.e. moving the cutterhead when it is not touching the rock at the face, usually during cutter changes). Gross thrust also includes impacts of TBM stiffness and losses in the hydraulic systems, but these should remain constant for any TBM.

Villeneuve (2008) showed that penetration curves highlight (Figure 5): (1) the minimum thrust required to begin advancing the TBM; (2) initial penetration behaviour dominated by grinding (creating fines); (3) the change from grinding to chipping (creating chips), called the critical thrust (Robbins, 1970), located at the inflection point; (4) the chipping efficiency, represented by the slope of the line past the inflection point; and (5) the point of steady-state penetration.

The steady-state penetration rate is limited by TBM design parameters, which define performance limits. The penetration limit is a function of muck conveyance, bucket design, cutter wear and maximum head revolution speed (Frenzel et al., 2012). The torque limit provides the transition from the penetration limit to the maximum thrust (Frenzel et al., 2008), which is a function of the rotational speed and is controlled by the maximum torque capacity. The thrust limit is controlled by cutter type, maximum thrust capacity and TBM head design. The penetration limit for the TBMs used in this investigation is ~11 mm/rev (Villeneuve, 2017). The torque limit for the TBMs in this study is ~30% of the maximum torque capacity (Villeneuve, 2017). The maximum net thrust on 432 mm cutters is ~250-267 kN (Frenzel et al., 2008; Maidl et al., 2008).

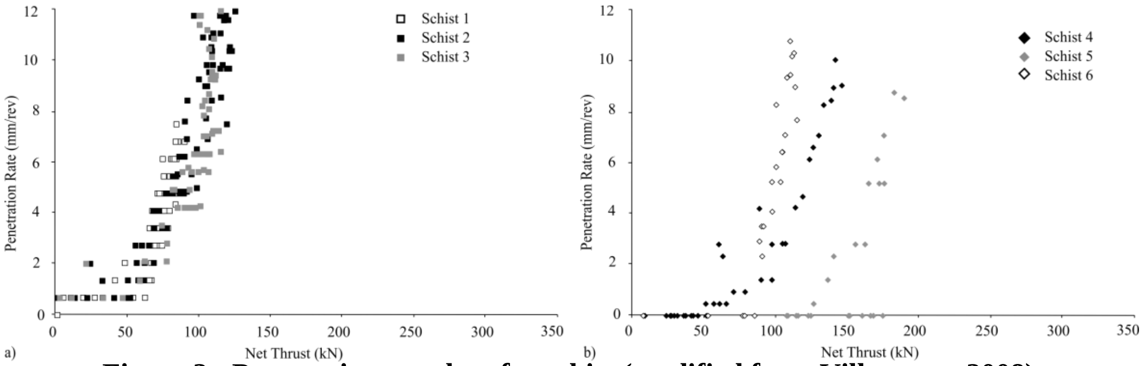

Figure 2: Penetration test data for schist (modified from Villeneuve, 2008).

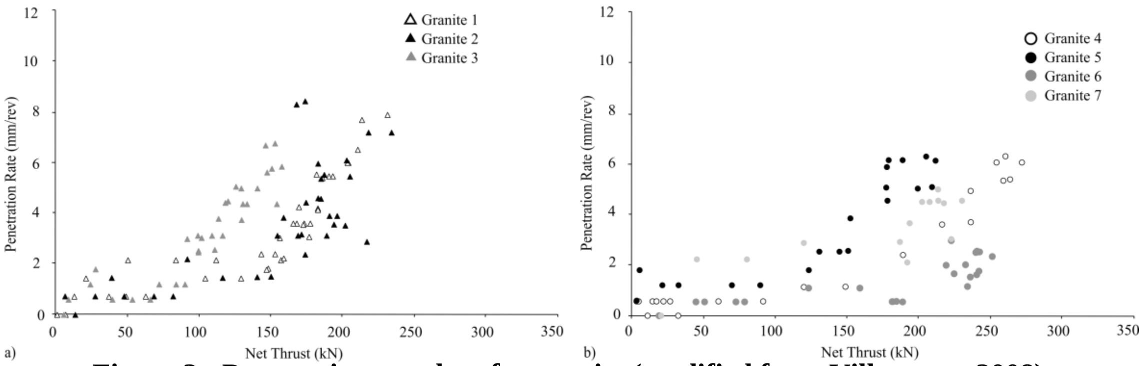

Figure 3: Penetration test data for granite (modified from Villeneuve, 2008).

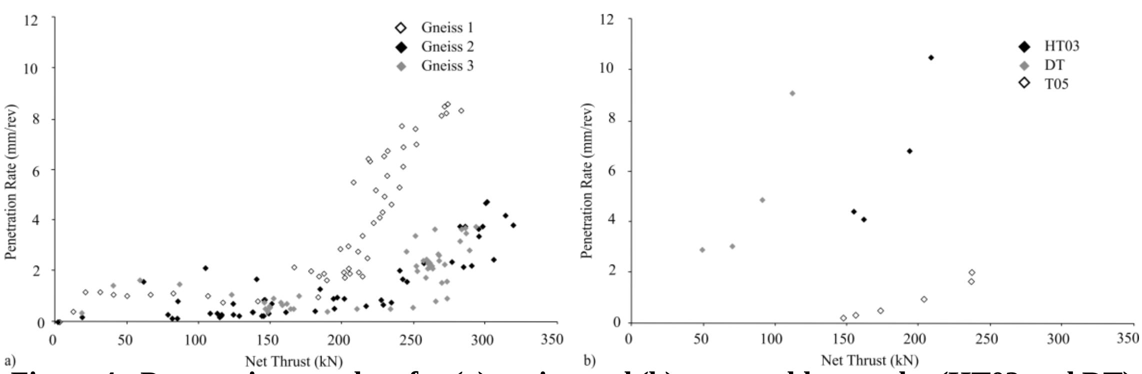

Figure 4: Penetration test data for (a) gneiss, and (b) two marble samples (HT03 and DT) tested in Yin et al. (2014) and one granite sample (T05) from Gong et al. (2007) (modified from Villeneuve, 2008).

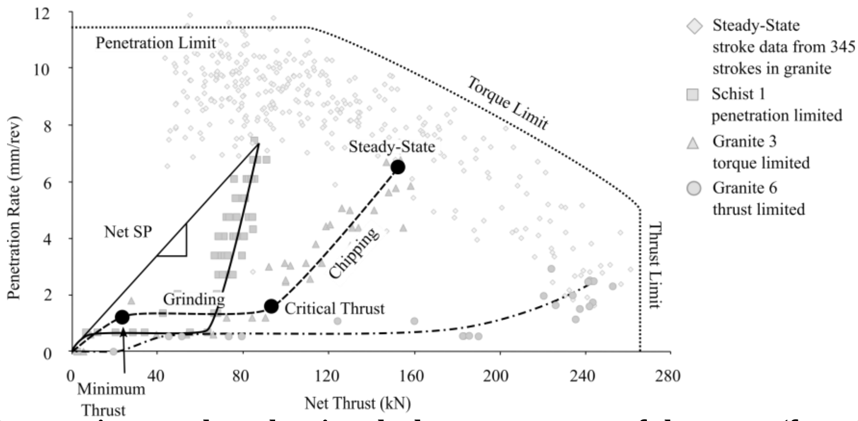

Figure 5: Penetration test data showing the key components of the curve (from Villeneuve, 2017).

3 PENETRATION TEST ANALYSIS

The minimum thrust and grinding portion of the penetration curve will depend on the resistance of the rock to crushing (Villeneuve, 2017). The critical thrust point and the slope of the curve during chipping (as discussed in Samuel and Seow (1984), Zhang et al. (2003) and Gehring (2009)), are related to rock strength and brittleness, mineralogy and fabric (Villeneuve et al., 2007, 2012; Villeneuve, 2008), and stress at the tunnel face (Yin et al., 2014). The location of the critical thrust and the slope and length of the curve beyond the critical thrust point are representative of the 100-200 mm thickness of rock over which the test is performed. Performing the test in different lithologies will produce different curves, which can be related back to the geological conditions.

The UCS values for the schist and granite in which the penetration tests were conducted show a strong relationship with critical thrust (Figure 6). The variance in these data likely results from fractures (pre-existing or stress-induced) in the face and variability at the metre scale in the rock strength. This shows that, while UCS can be used to identify rocks that are at risk of poor excavation performance, penetration tests are required to identify the actual point at which chipping occurs.

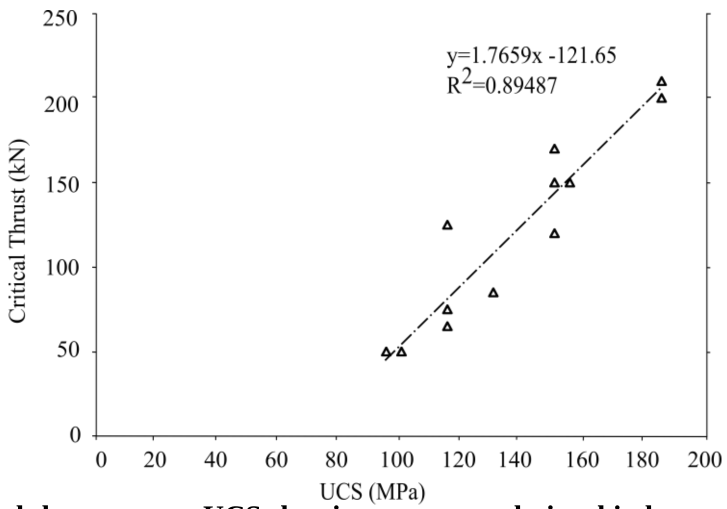

Figure 6: Critical thrust versus UCS showing a strong relationship between rock strength and thrust at transition from grinding to chipping.

The penetration curves in the schist, gneiss and granite are grouped in Figure 7 according to the dominant excavation mode. The curves for Schists 4 and 5 have the lowest strength (115 MPa (Villeneuve, 2017)) and low critical thrust, with chipping-dominated excavation. The curves for

Granites 2, 5 and 7 have moderate strength between 150-185 MPa (Villeneuve, 2017) and tend to have a critical thrust between 100 kN and 200 kN (Figure 7). The curves above the critical thrust are torque limited, showing that chipping was occurring, but not very efficiently. The curves with critical thrust above 200 kN (Granites 4 and 6, T05, and Gneiss 2 and 3 in Figure 7) are very short with shallow slope, and are limited by the cutter thrust. The high critical thrust shows that minimal chipping is occurring due to high strength (Granite 4 = 150 MPa, Granite 6 = 185 MPa and T05 = 175 MPa (Villeneuve, 2017)), with excavation dominated by grinding.

The critical thrust and the slope of the penetration curve above the critical thrust are key indicators of cutter efficiency, which are controlled by the strength (Figure 6) and ease of propagation of newly initiated fractures. Geological characteristics play an important role in both the strength and the ability to propagate fractures (Villeneuve, 2017). An easy transition to tensile fracturing processes (chipping) occurs in Schist 4 (Figure 8), which has a well-defined micaceous (40%) cleavage that facilitates fracture propagation (Villeneuve et al., 2012). A less efficient transition to tensile fracturing, and thus less chipping, occurs in Granite 2 (Figure 8), which has a poorly defined micaceous (15%) schistosity. Grinding occurs in Granite 6 (Figure 8), which has very low mica content (5%) and no foliation. As demonstrated by Granites 2 and 6, geological characteristics, such as fabric and mica content, are especially important for rocks with moderate to high critical thrust, where the ability to propagate fractures can make a large difference in the resulting penetration rate (i.e. torque limited rather than thrust limited).

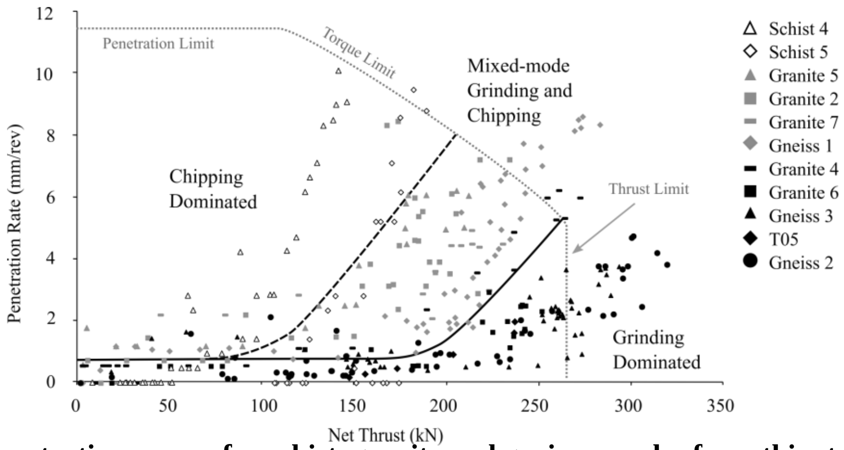

Figure 7: Penetration curves for schist, granite and gneiss samples from this study and one granite sample from Gong et al. (2007) excavated under stable face conditions overlaid by the performance limits from Fig. 5 (from Villeneuve, 2017).

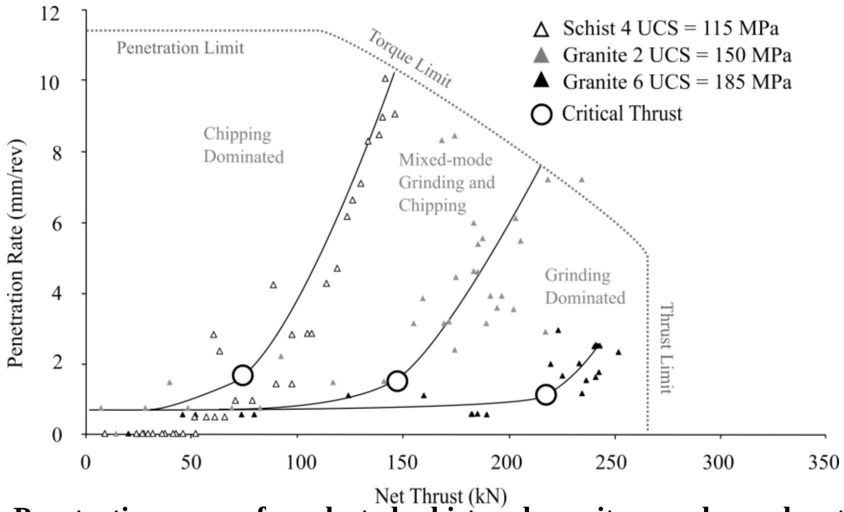

Figure 7: Penetration curves for selected schist and granite samples under stable face conditions showing the location of critical thrust overlaid by the performance limits from Figure 5, and excavation types from Figure 7 (from Villeneuve, 2017).

4 DISCUSSION

The penetration graphs in Figures 2-4 show that the transition from grinding to chipping does not consistently occur at 1 mm/rev. Manual analysis is required to determine the inflection point for critical thrust. Depending on the quality of the penetration test data, in particular the density of data points defining the start-up curve, it is not always possible to identify the critical thrust (e.g. Figure 4b). For this reason, a precision of 5 kN was selected for critical thrust for the tests in this study (Villeneuve, 2017), in Yin et al. (2014) and in Gong et al. (2007). Considering the ease with which the critical thrust can be obtained with good penetration test data it provides an easy method to identify the transition from grinding to chipping.

The findings from this research can be used to provide guidance to aid in drawing up contract documents and selecting the method by which TBM performance will be used for payment and progress assessment, depending on the anticipated geomechanical and geological conditions. During construction, penetration tests can be used to provide guidance to TBM operators regarding thrust application. In a rock type similar to Granite 6, which tends to be excavated via the grinding process, very little gain in penetration rate can be achieved by applying higher thrust, and wear and cutter damage could be minimised by lowering the thrust without substantially reducing penetration rate. Chipping-dominated excavation may never be achieved in these rock types with very high strength, even if cutter thrust limits were increased, as the process will remain too energy intensive due to the high fracture initiation threshold and the poor fracture propagation in these rocks.

5 CONCLUSIONS

This research focused on the determination of the impact of intact rock characteristics at the tunnel face on the rock cutting process. It was demonstrated that TBM penetration tests can provide a measure of TBM performance. Critical thrust can provide an understanding of the transition from grinding to chipping.

Penetration test data were used to categorise penetration-thrust graphs according to TBM operational constraints and the excavation performance from grinding-dominated, through mixed-mode grinding and chipping, to chipping-dominated. Using these categorised graphs, it was shown that rocks with higher strength tend to be excavated through the grinding-dominated process. For massive rock masses with significantly high strength, over 175 MPa in this study, only minor gains in penetration rate can be achieved through increased thrust because the critical thrust approaches the cutter thrust limit of 267 kN for commonly used 432 mm (17 inch) cutters. Penetration testing can help TBM operators identify whether additional thrust is warranted in individual rocks masses with low penetration rates during excavation.

This research has also shown that geological characteristics, in addition to rock strength, play an important role in both the chipping process and stress-induced face instability. Under similar stress conditions, rocks with well-defined fabric, oriented oblique to the tunnel face were easier to excavate than rocks without fabric or fabric oriented perpendicular to the face.

The penetration test methodology can be used for further investigation into the rock cutting process, to aid in developing better penetration rate prediction tools, and as a measure of TBM performance for tunnelling contract management during excavation. We have shown that our methodologies provide repeatable results using data from Gong et al. (2007) and Yin et al. (2014). For these data to be comparable across projects, a consistent testing methodology should be used, for example the methodology set out in Gong et al. (2007) or in Frenzel et al. (2012).

6 ACKNOWLEDGEMENTS

This work was supported by Herrenknecht AG, a Postgraduate Scholarship from the Natural Science and Engineering Research Council (NSERC) of Canada and the Golder Associates (Canada) Visitor Programme to the Queen’s Geo-Engineering Centre. Murer-Strabag and Tunnel Alp Transit consortia are also thanked for their in-kind support during penetration testing and data collection.

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